

Non-meridional epimorphisms of knot groups

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Abstract. In the literature of the study of knot group epimorphisms, the existence of an epimorphism between two given knot groups is mostly (if not always) shown by giving an epimorphism which preserves meridians. A natural question arises: is there an epimorphism preserving meridians whenever a knot group is a homomorphic image of another? We answer in the negative by presenting infinitely many pairs of prime knot groups (G, G') such that G' is a homomorphic image of G but no epimorphism of G onto G' preserves meridians.

1. Introduction

For a knot K in S^3 , its *knot group* $G(K)$ is defined by $G(K) = \pi_1(S^3 - K)$. The study of knot groups has long history, from the beginning of modern knot theory. In particular, recently, *epimorphisms* of knot groups have been receiving much attention. A key problem is to determine when there is an epimorphism between two knot groups. For prime knots, which are of the most interest, it is well known that a partial order \geq is obtained by defining $K \geq K'$ if there is an epimorphism $G(K) \rightarrow G(K')$ (see, for instance, [ORS08, p. 422]).

There is a fair amount of recent work on this in the literature. In their remarkable work [AL12], Agol and Liu proved a long-standing conjecture of Simon that a knot group surjects onto only finitely many knot groups. It follows that for any prime knot K , there are only finitely many prime knots less than or equal to K . Together with Kitano, Horie, and Matsumoto, the second author investigated pairs of prime knots with 11 crossings or less whose knot groups admit epimorphisms [KS05, HKMS11, KSW05, KSW11]. In particular, they constructed many explicit examples of epimorphisms between knot groups. González-Acuña and Ramírez studied which knot groups (particularly those of 2-bridge knots) admit epimorphisms onto torus knot groups [GAR01, GAR03]. In work of Ohtsuki, Riley, and Sakuma [ORS08], Hoste and Shanahan [HS10], and Lee and Sakuma [LS12], systematic constructions of epimorphisms between 2-bridge knot (and link) groups were presented and studied. In [SW06, SW08], Silver and Whitten studied knot group epimorphisms preserving peripheral structure; in particular they showed that such epimorphisms give rise to a partial order on the set of all knots.

Meridional epimorphisms

Interestingly, most (if not all) results in the literature that a knot is less than or equal to another are shown by presenting an epimorphism which preserves meridians. To be more precise, we use the following terms: we call an element $[\alpha] \in G(K)$ a *meridian* if α is freely homotopic to a meridian curve lying on the boundary of a tubular neighborhood of K , and we say that a homomorphism $G(K) \rightarrow G(K')$ is *meridional* if a meridian in $G(K)$ is

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sent to a meridian in $G(K')$. In this paper knots are unoriented, so that a meridian may be endowed with any orientation.

The following natural question arises:

Question. Is there a meridional epimorphism $G(K) \rightarrow G(K')$ whenever there is an epimorphism $G(K) \rightarrow G(K')$?

We remark that it does not ask whether all knot group epimorphisms are meridional; it is known that there exist non-meridional epimorphisms of knot groups. For instance see work of Johnson and Livingston [JL89]. We also remark that meridional epimorphisms can be related to geometric properties, for example, periods of knots and degree one maps between knot exteriors. See [KS08] for details.

There are several results supporting an affirmative answer to the above question. For any previously known example of a knot group $G(K)$ which admits an epimorphism onto $G(K')$, there exists a meridional epimorphism of $G(K)$ onto $G(K')$. In particular, all the epimorphisms found in [KS05, HKMS11, KSW05, KSW11] for groups of prime knots with 11 or less crossings are meridional. For torus knot groups, there is a meridional epimorphism whenever there is an epimorphism [SW08]. Also, the knot group epimorphisms in [GAR01, GAR03, ORS08, LS12] are all meridional. An epimorphism between nontrivial knot groups preserving peripheral structure in the sense of [SW06, SW08] are known to be meridional [SW06, Proof of Theorem 4.1], [HS10, Theorem 2.1]. We also remark that epimorphisms preserving peripheral structure, particularly meridional epimorphisms of prime knot groups, can be studied via maps of 3-manifolds with well-defined degree.

Our main result is, nevertheless, that the answer is in the negative.

Theorem 1.1. *There are infinitely many distinct pairs of prime knots (K, K') for which there is an epimorphism of $G(K)$ onto $G(K')$ but there is no meridional epimorphism of $G(K)$ onto $G(K')$.*

The proof of Theorem 1.1 proceeds as follows. In Section 2, we give constructions of pairs of knot groups which admit non-meridional epimorphisms. In Section 3, we detect the non-existence of meridional epimorphisms using twisted Alexander polynomials. This method allows us to obtain finitely many (in fact two) “seed” examples. We remark that it depends on heavy computation infeasible by hand, and hence it seems unable to detect infinitely many cases in this way. In Section 4, we present a geometric method to produce, from the seed examples, infinitely many pairs of knot groups which admit non-meridional epimorphisms but do not admit meridional epimorphisms. In Appendix A, we present computational results of certain twisted Alexander polynomials which are used to prove the non-existence of a meridional epimorphism.

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2. Construction of non-meridional knot group epimorphisms

In this section we give certain explicit examples non-meridional epimorphisms of knot groups, for some of which we will show the non-existence of meridional epimorphisms in the next section.

2.1. First example on the trefoil knot

In this subsection we describe the first successful example of a pair of knots satisfying Theorem 1.1, which we indeed found by ad-hoc trial and error attempts aided by a computer.

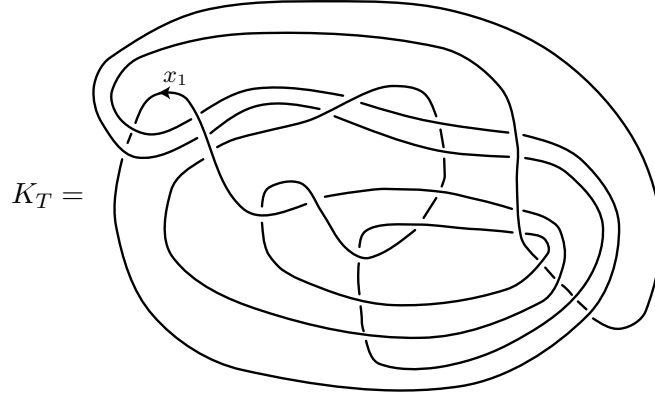


FIGURE 1. A knot K_T .

Consider the knot K_T shown in Figure 1. The Wirtinger presentation of the knot group $G(K_T)$ obtained from Figure 1 has 24 generators x_1, x_2, \dots, x_{24} , and 24 relators

$$\begin{array}{cccc}
 x_6 x_2 \bar{x}_6 \bar{x}_1, & x_{10} x_2 \bar{x}_{10} \bar{x}_3, & x_6 x_3 \bar{x}_6 \bar{x}_4, & x_{22} x_4 \bar{x}_{22} \bar{x}_5, \\
 x_1 x_6 \bar{x}_1 \bar{x}_5, & x_{17} x_7 \bar{x}_{17} \bar{x}_6, & x_{23} x_7 \bar{x}_{23} \bar{x}_8, & x_{13} x_9 \bar{x}_{13} \bar{x}_8, \\
 x_3 x_9 \bar{x}_3 \bar{x}_{10}, & x_1 x_{10} \bar{x}_1 \bar{x}_{11}, & x_{22} x_{12} \bar{x}_{22} \bar{x}_{11}, & x_6 x_{13} \bar{x}_6 \bar{x}_{12}, \\
 x_{23} x_{14} \bar{x}_{23} \bar{x}_{13}, & x_{17} x_{14} \bar{x}_{17} \bar{x}_{15}, & x_{18} x_{16} \bar{x}_{18} \bar{x}_{15}, & x_6 x_{17} \bar{x}_6 \bar{x}_{16}, \\
 x_1 x_{17} \bar{x}_1 \bar{x}_{18}, & x_{16} x_{19} \bar{x}_{16} \bar{x}_{18}, & x_{24} x_{19} \bar{x}_{24} \bar{x}_{20}, & x_{12} x_{21} \bar{x}_{12} \bar{x}_{20}, \\
 x_4 x_{21} \bar{x}_4 \bar{x}_{22}, & x_1 x_{23} \bar{x}_1 \bar{x}_{22}, & x_6 x_{23} \bar{x}_6 \bar{x}_{24}, & x_{18} x_{24} \bar{x}_{18} \bar{x}_1.
 \end{array}$$

Here the generators are ordered along the orientation, starting from the generator x_1 shown in Figure 1. In the relators \bar{x} denotes the inverse of x .

Recall that the trefoil knot T has the following Wirtinger presentation:

$$G(T) = \langle y_1, y_2 \mid y_1 y_2 y_1 = y_2 y_1 y_2 \rangle.$$

We define a map $f: G(K_T) \rightarrow G(T)$ as follows:

$$\begin{aligned}
f(x_1) &= y_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{13}) &= y_1 y_2 \bar{y}_1 y_2 \bar{y}_1, \\
f(x_2) &= y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 y_1^3 y_2^3 \bar{y}_1 y_2 \bar{y}_1, & f(x_{14}) &= y_1 \bar{y}_2 y_1 \bar{y}_2^3 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2^3 \bar{y}_1 y_2 \bar{y}_1, \\
&\quad \cdot \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{15}) &= y_1 y_2 \bar{y}_1 y_2 \bar{y}_1, \\
f(x_3) &= y_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{16}) &= y_1 \bar{y}_2^2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2^2 \bar{y}_1, \\
f(x_4) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 y_1 \bar{y}_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{17}) &= y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 \bar{y}_2 y_1 y_2 \bar{y}_1 \\
f(x_5) &= y_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 y_1 \bar{y}_2 \bar{y}_1 y_2, & &\quad \cdot y_2 \bar{y}_1 y_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1, \\
f(x_6) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{18}) &= y_2^2 \bar{y}_1, \\
f(x_7) &= y_1 \bar{y}_2 y_1 \bar{y}_2^3 y_1 y_2^2 \bar{y}_1 \bar{y}_1 y_2^3 \bar{y}_1 y_2 \bar{y}_1, & f(x_{19}) &= y_1 \bar{y}_2^2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2^3 \bar{y}_1 y_2 \bar{y}_1 y_2^2 \bar{y}_1, \\
f(x_8) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{20}) &= y_2^2 \bar{y}_1, \\
f(x_9) &= y_1 \bar{y}_2 y_1 \bar{y}_2^2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 & f(x_{21}) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2 \bar{y}_1 \\
&\quad \cdot y_2^2 \bar{y}_1 y_2 \bar{y}_1, & &\quad \cdot y_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 y_1 \bar{y}_2 \bar{y}_1 y_2 \bar{y}_1, \\
f(x_{10}) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1, & f(x_{22}) &= y_2^2 \bar{y}_1, \\
f(x_{11}) &= y_1 y_2 y_2 \bar{y}_1^2, & f(x_{23}) &= y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2^3 \bar{y}_1 y_2 \bar{y}_1, \\
f(x_{12}) &= y_1 \bar{y}_2^2 y_1 y_2^2 \bar{y}_1^2 y_2^2 \bar{y}_1, & f(x_{24}) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 \bar{y}_1 y_2^2 y_1 \bar{y}_2 \bar{y}_1 y_2 \bar{y}_1.
\end{aligned}$$

Theorem 2.1. *The map $f: G(K_T) \rightarrow G(T)$ is a non-meridional epimorphism.*

Proof. It is shown that f is a group homomorphism, by directly verifying that the relators of $G(K_T)$ vanish under f . For instance we have

$$\begin{aligned}
f(x_6 x_2 \bar{x}_6 \bar{x}_1) &= y_1 \bar{y}_2 y_1 y_1 \bar{y}_1 y_1 \bar{y}_1 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_1^3 \bar{y}_1 y_1 \bar{y}_1 \bar{y}_1 \\
&\quad \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_1 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 = e \\
f(x_{10} x_2 \bar{x}_{10} \bar{x}_3) &= y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2^3 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1 \\
&\quad \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 = e
\end{aligned}$$

and so forth.

To show that f is an epimorphism, we explicitly describe elements of $G(K_T)$ which are sent to generators of $G(T)$:

$$\begin{aligned}
f(x_{18} x_6 \bar{x}_1 \bar{x}_1 x_{18} x_6 \bar{x}_1) &= y_2^2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 y_2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 \\
&\quad \cdot y_2^2 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 \bar{y}_1 \bar{y}_1 \cdot y_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 \\
&= y_2 y_1 y_2 \bar{y}_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_2 y_1 y_2 \bar{y}_1 \bar{y}_1 \\
&= y_1 y_2 y_1 \bar{y}_1 \bar{y}_2 y_1 \bar{y}_2 \bar{y}_1 y_1 y_2 y_1 \bar{y}_1 \bar{y}_1 = y_1.
\end{aligned}$$

Similarly we have the following:

$$f(x_1 \bar{x}_6 \bar{x}_{18} x_1 x_{18} x_6 \bar{x}_1^2 x_{18} x_6 \bar{x}_1) = y_2.$$

Although we will show that there is no meridional epimorphism of $G(K_T)$ onto $G(T)$ in the next section, we present here a simple direct proof that our f is not meridional. Define a representation $\rho: G(T) \rightarrow \text{SL}(2, \mathbb{Z})$ by

$$\rho(y_1) = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad \rho(y_2) = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}.$$

It is straightforward to verify that ρ is well-defined. The image of $f(x_1)$ under ρ is given by

$$\rho(f(x_1)) = \rho(y_1 y_2 \bar{y}_1 y_2 \bar{y}_2) = \begin{bmatrix} -1 & 2 \\ -3 & 5 \end{bmatrix}.$$

It has trace 4, while the trace of $\rho(y_1)$ is 2. It follows that the image $f(x_1)$ of the meridian x_1 of K_T is not conjugate to the meridian y_1 of T . \square

We remark that K_T is a hyperbolic knot, according to SnapPy [CDW], and consequently, K_T is prime.

2.2. Construction using normal generators and Johnson's method

To describe the second succesful example satisfying Theorem 1.1, we employ a more systematic construction which combines algebraic computations in knot groups and geometric realization arguments. In the first step we construct a non-meridional normal generator, and in the second step, we construct knot group homomorphisms realizing the normal generator as the image of a meridian.

Finding pseudo-meridian: twist knots. It is well known that a meridian is a normal generator of a knot group. We call a normal generator of a knot group a *pseudo-meridian*, that is, $w \in G(K)$ is called a pseudo-meridian if $G(K)/\langle w \rangle$ is trivial, where $\langle w \rangle$ is the normal closure of w .

We will present useful pseudo-meridians of twist knots. Let $J(2, 2q)$ be the twist knot shown in Figure 2 ($q \in \mathbb{Z}$). For example, $J(2, 0)$ is the trivial knot, $J(2, 2)$ is the trefoil knot, and $J(2, -2)$ is the figure eight knot. The presentation of $G(J(2, 2q))$ is given by

$$G(J(2, 2q)) = \langle a, b \mid w^q a = b w^q \rangle, \quad w = [b, a^{-1}].$$

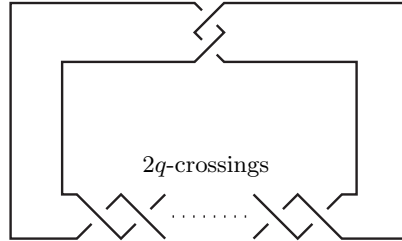


FIGURE 2. The twist knot $J(2, 2q)$.

Proposition 2.2. *Let*

$$g_1 = \begin{cases} w^q a & \text{if } q > 0, \\ \bar{w}^q b & \text{if } q < 0. \end{cases}$$

Then g_1 is a pseudo-meridian, but not a meridian for $q \neq 0$.

Proof. First we show that g_1 is a pseudo-meridian by verifying that $G(J(2, 2q))/\langle g_1 \rangle$ is trivial. In the quotient, $g_1 = e$, that is, $w^q = \bar{a}$ if $q > 0$. Then the relation of the twist knot group gives $\bar{a}a = b\bar{a}$. This implies that $b = a$ and $w = [b, \bar{a}] = e$. Therefore $a = b = \bar{w}^q = e$. Hence g_1 is a pseudo-meridian. Similarly, we can show that $g_1 = \bar{w}^q b$ is a pseudo-meridian for $q < 0$.

Next we show that g_1 is not conjugate to a , that is, g_1 is not a meridian of the twist knot. Let $\rho : G(J(2, 2q)) \rightarrow SL(2, \mathbb{C})$ be defined by

$$\rho(a) = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad \rho(b) = \begin{bmatrix} 1 & 0 \\ -u & 1 \end{bmatrix}, \quad u \in \mathbb{C} - \{0\}.$$

We set $\phi_q(u)$ by the $(1, 1)$ -entry of $\rho(w^q)$. It is easy to see that if $u = 0$, then ρ is not a representation. More precisely, Riley [Ril72] showed that ρ is a non-abelian parabolic representation if and only if $\phi_q(u) = 0$. Moreover, Hoste-Shanahan [HS01] proved that $\phi_q(u)$ is irreducible and that $\deg \phi_q(u)$ is $2q - 1$ if $q > 0$ and $2|q|$ if $q < 0$.

We define a polynomial $p_q(u)$ by

$$p_q(u) = \begin{cases} \text{tr}(\rho(w^q a)) - \text{tr}(\rho(a)) = \text{tr}(\rho(w^q a)) - 2 & \text{if } q > 0, \\ \text{tr}(\rho(\bar{w}^q b)) - \text{tr}(\rho(a)) = \text{tr}(\rho(\bar{w}^q b)) - 2 & \text{if } q < 0. \end{cases}$$

First, consider the case $q > 0$. Caley-Hamilton theorem gives us

$$\rho(w)^2 - (\text{tr } \rho(w))\rho(w) + I = 0.$$

The trace of $\rho(w)$ is $u^2 + 2$. Multiplying both sides by $\rho(w^{q-2}a)$, we obtain

$$\rho(w^q a) = (u^2 + 2)\rho(w^{q-1}a) - \rho(w^{q-2}a).$$

Taking the trace of the both sides and using the definition of $p_q(u)$, we obtain a recursion formula for $p_q(u)$:

$$p_q(u) = (u^2 + 2)p_{q-1}(u) - p_{q-2}(u) + 2u^2$$

(cf. [HS01]). Since $p_1(u) = 2u^2$ and $p_2(u) = 2u^4 + 6u^2$, we conclude that $p_q(u)$ has a factor u^2 and $\deg p_q(u)$ is $2q$. Then $p_q(u)$ can be written as

$$p_q(u) = u^2 \bar{p}_q(u)$$

and the degree of $\bar{p}_q(u)$ is $2q - 2$, which is less than $\deg \phi_q(u)$. Since $\phi_q(u)$ is irreducible, $\phi_q(u)$ does not have a multiple root, that is, $\phi_q(u)$ has distinct $2q - 1$ roots, which are not zero. Hence there exists at least one root $u \in \mathbb{C}$ of $\phi_q(u) = 0$ such that $p_q(u) \neq 0$, namely,

$$\text{tr}(\rho(w^q a)) \neq \text{tr}(\rho(a)).$$

This implies $w^q a$ is not conjugate with a . Similarly, we prove the statement for the case $q < 0$. The recursion formula of $p_q(u)$ is given by

$$p_q(u) = (u^2 + 2)p_{q+1}(u) - p_{q+2}(u) + 2u^2.$$

By straightforward computation, $p_{-1}(u) = 0$ and $p_{-2}(u) = 2u^2$. Then the same argument as the case $q > 0$ holds. Therefore $\bar{w}^q b$ is not conjugate with a . This completes the proof. \square

We can produce a generating set of the twist knot group by conjugating g_1 . In the case $q > 0$, the relation can be written as $(g_1 \bar{a})a = b(g_1 \bar{a})$. Then $b = ga\bar{g}_1$ and

$$w = [b, \bar{a}] = g_1 a \bar{g}_1 \cdot \bar{a} \cdot g_1 \bar{a} \bar{g}_1 \cdot a = [g_1, a][g_1, \bar{a}].$$

Therefore we obtain

$$\begin{aligned} a &= ([\bar{a}, g_1][a, g_1])^q g \\ &= \bar{a} g_1 a \cdot \bar{g}_1 \cdot a g_1 \bar{a} \cdot \bar{g}_1 \cdots \bar{a} g_1 a \cdot \bar{g}_1 \cdot a g_1 \bar{a} \\ &= (g_2 \bar{g}_1 g_3 \bar{g}_1)^{q-1} g_2 \bar{g}_1 g_3, \end{aligned}$$

where $g_2 = \bar{a} g_1 a$ and $g_3 = a g_1 \bar{a}$. It follows that $G(J(2, 2q))$ is generated by the three conjugate elements g_1 , g_2 , and g_3 .

Similarly, in the case $q < 0$, we can show that $G(J(2, 2q))$ is generated by the three conjugate elements $g_1, g_2 = \bar{b}g_1b, g_3 = bg_1\bar{b}$. Here b can be expressed as $(g_3\bar{g}_1g_2\bar{g}_1)^qg_1$.

Johnson's method for knot group epimorphs. González-Acuña and Johnson showed independently the following.

Theorem 2.3 ([GA75, Joh80]). *Let G be a group finitely generated by the conjugates of $g \in G$. Then there is a knot with group $G(K)$ and meridian $\mu \in G(K)$, and a homomorphism φ of $G(K)$ onto G carrying μ onto g .*

Johnson gave a proof of this result by presenting a process to construct such a knot K . Here we review this process.

By hypothesis, G is finitely generated and normally generated by g . Thus we can choose finitely many generators of the form $g_1 = g, g_2 = w_2g\bar{w}_2, \dots, g_n = w_ng\bar{w}_n$. Take a trivial link with n components, and label the components by g_1, g_2, \dots, g_n . For each $i \geq 2$, we connect the component g_i to g_1 along a band which represent the word w_i ; for example, if $w_2 = g_1\bar{g}_3$, we connect the first circle and the second circle as in Figure 3. Let K be the resulting knot. Then it is not too difficult to see that $G(K)$ satisfies the conclusion of Theorem 2.3.

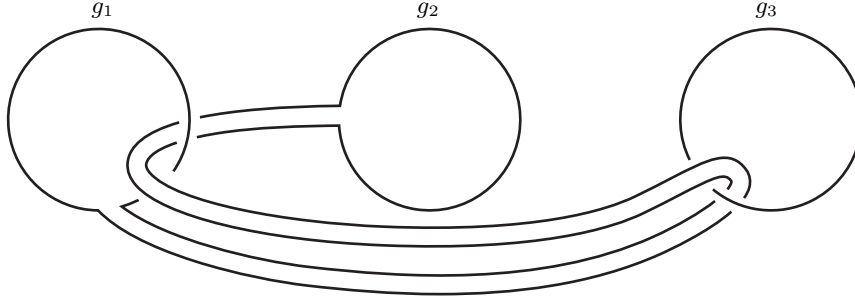


FIGURE 3. The connecting band for $w_2 = g_1\bar{g}_3$.

For the twist knot group $G(J(2, 2q))$, we use the pseudo-meridian g_1 defined in Proposition 2.2. By the above process of Theorem 2.3, we can construct a knot J_q for which there exists an epimorphism $\varphi: G(J_q) \rightarrow G(J(2, 2q))$ that sends a meridian of J_q to the pseudo-meridian g_1 of $J(2, 2q)$. In particular, φ is non-meridional.

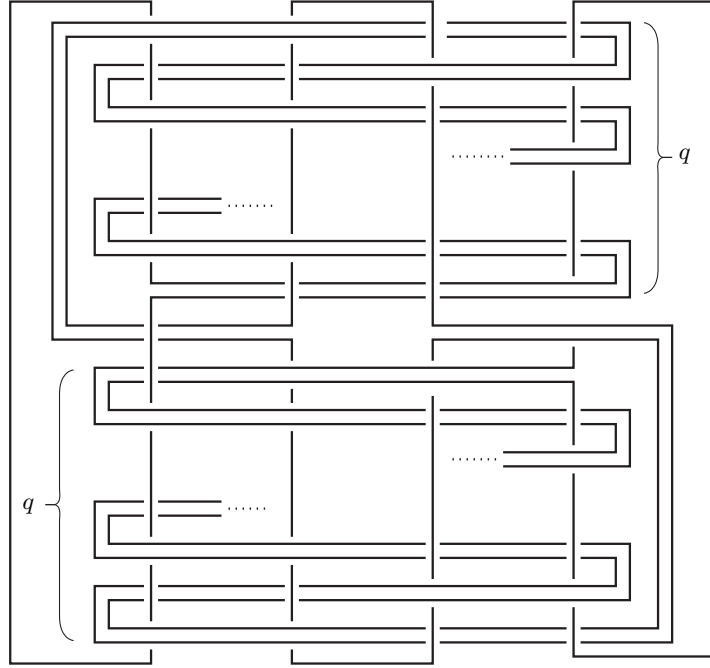


FIGURE 4. The knot J_q ($q > 0$).

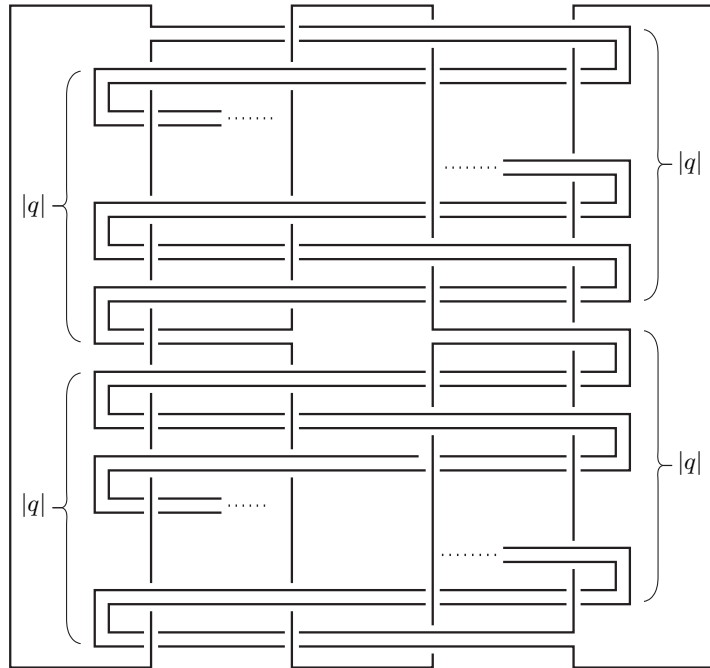


FIGURE 5. The knot J_q ($q < 0$).

3. Twisted Alexander polynomial and nonexistence of meridional epimorphisms

In this section we show that two of the examples described in Section 2 do not admit any meridional epimorphisms. For this purpose we use twisted Alexander polynomials, as discussed below.

3.1. Obstructions to admitting a meridional epimorphism

We recall the definition of the twisted Alexander polynomial following Wada [Wad94]. For this purpose, temporarily, we assume that a knot is oriented. For brevity, although any presentation of a knot group can be used in general, we will consider only the special case of a deficiency one presentation

$$G = \langle x_1, \dots, x_k \mid r_1, \dots, r_{k-1} \rangle$$

of a knot group $G = G(K)$ in which each generator x_i represent a positively oriented meridian. For instance a Wirtinger presentation can be used. Suppose $\rho: G \rightarrow \mathrm{SL}(n, \mathbb{F})$ is a representation over a field \mathbb{F} . Let $\alpha: G \rightarrow \mathbb{Z} = \langle t \rangle$ be the surjection defined by $\alpha(x_i) = t$. The tensor representation $\rho \otimes \alpha$ defined by $(\rho \otimes \alpha)(g) = \alpha(g) \cdot \rho(g)$ gives rise to a ring homomorphism $\mathbb{Z}[G] \rightarrow M_n(\mathbb{F}[t, t^{-1}])$. Let $F\langle x_i \rangle$ be the free group generated by the symbols x_1, \dots, x_k , and let Φ be the composition

$$\Phi: \mathbb{Z}[F\langle x_i \rangle] \xrightarrow{\text{proj.}} \mathbb{Z}[G] \xrightarrow{\rho \otimes \alpha} M_n(\mathbb{F}[t, t^{-1}]).$$

Viewing r_i as an element of $F\langle x_i \rangle$, the Fox derivative $\frac{\partial r_i}{\partial x_j} \in \mathbb{Z}[F\langle x_i \rangle]$ is defined as in [Fox53]. The matrix consisting of $(k-1) \times k$ blocks of size $n \times n$

$$\Phi\left(\frac{\partial r_i}{\partial x_j}\right) \in M_n(\mathbb{F}[t, t^{-1}]), \quad 1 \leq i \leq k-1, 1 \leq j \leq k$$

is called a *twisted Alexander matrix*. It can be verified that $\det \Phi(1 - x_j) \neq 0$ for some j (see [Wad94, Lemma 2]). For such an index j , let M_j be the matrix obtained from the twisted Alexander matrix by deleting the blocks on the j th column. Viewing M_j as an $n(k-1) \times n(k-1)$ matrix over $\mathbb{F}[t, t^{-1}]$, we define the *twisted Alexander polynomial* for (K, ρ) by $\Delta_{K, \rho} = \Delta_{K, \rho}^N / \Delta_{K, \rho}^D$ where

$$\Delta_{K, \rho}^N = \det(M_j), \quad \Delta_{K, \rho}^D = \det \Phi(x_j - 1).$$

We call $\Delta_{K, \rho}^N$ and $\Delta_{K, \rho}^D$ the *numerator* and *denominator* of the twisted Alexander polynomial. Note that $\Delta_{K, \rho}^N$ and $\Delta_{K, \rho}^D$ are Laurent polynomials in $\mathbb{F}[t, t^{-1}]$.

Under our assumption that the generators of the presentation for G are positive meridians, both polynomials $\Delta_{K, \rho}^N$ and $\Delta_{K, \rho}^D$ are well-defined invariants of (K, ρ) , up to multiplication by units in $\mathbb{F}[t, t^{-1}]$. It is a consequence of the following two facts: (i) the fraction $\Delta_{K, \rho}$ is well-defined up to units for any choice of a presentation of G (e.g. see [Wad94]), and (ii) $\Delta_{K, \rho}^D = \det \Phi(x_j - 1)$ is determined, up to units, by the conjugacy class of the generator x_j .

Remark 3.1. By the same argument, the following more general statement is true: for a finitely presentable group G and a conjugacy class c , the numerator and denominator of the twisted Alexander polynomial of G are invariants of (G, c) , provided that we use a presentation whose generators are in the conjugacy class c .

Remark 3.2. For an unoriented knot K , $\Delta_{K,\rho}^N$ and $\Delta_{K,\rho}^D$ are well-defined up to the substitution $t \rightarrow t^{-1}$ (and up to multiplication by a unit). For our purpose, it does not cause any problem.

The following is the key ingredient we use to detect the non-existence of a meridional epimorphism.

Theorem 3.3 (Kitano-Suzuki-Wada [KSW05, KSW11]). *Suppose there is a meridional epimorphism $G(K) \rightarrow G(K')$. Then for any representation $\rho': G(K') \rightarrow \mathrm{SL}(n, \mathbb{F})$ over a field \mathbb{F} , there is a representation $\rho: G(K) \rightarrow \mathrm{SL}(n, \mathbb{F})$ such that for some $\epsilon \in \{1, -1\}$, $\Delta_{K',\rho'}^N(t)$ divides $\Delta_{K,\rho}^N(t^\epsilon)$ in $\mathbb{F}[t, t^{-1}]$ and $\Delta_{K',\rho'}^D(t)$ is equal to $\Delta_{K,\rho}^D(t^\epsilon)$ up to units.*

Remark 3.4.

- (1) The representation ρ in Theorem 3.3 is the composition of the given meridional epimorphism and ρ' . Since our aim is to detect the non-existence of a meridional epimorphism, we do not know what ρ would be. Consequently, to use Theorem 3.3, we need to investigate all representations $\rho: G(K) \rightarrow \mathrm{SL}(n, \mathbb{F})$ such that $\mathrm{Im} \rho = \mathrm{Im} \rho'$ and $\rho(\text{meridian of } K)$ is conjugate to $\rho(\text{meridian of } K')$ in $\mathrm{Im} \rho'$.
- (2) Under the weaker assumption that there is an epimorphism $G(K) \rightarrow G(K')$, which might be non-meridional, we have a weaker conclusion that $\Delta_{K',\rho'}(t)$ divides $\Delta_{K,\rho}(t^\epsilon)$. See [KSW05, KSW11].

3.2. Computation for the first example on the trefoil

In this subsection we show that there is no meridional epimorphism of the knot group $G(K_T)$ onto the trefoil group $G(T)$, where K_T is the knot presented in Figure 1.

We will use representations over $\mathrm{SL}(2, \mathbb{F}_5)$. In particular, consider a representation

$$\rho': G(T) = \langle y_1, y_2 \mid y_1 y_2 y_1 = y_2 y_1 y_2 \rangle \longrightarrow \mathrm{SL}(2, \mathbb{F}_5)$$

defined by

$$\rho'(y_1) = \begin{bmatrix} 0 & 4 \\ 1 & 3 \end{bmatrix}, \quad \rho'(y_2) = \begin{bmatrix} 0 & 1 \\ 4 & 3 \end{bmatrix}.$$

It is straightforward to verify that the relator is sent to the identity.

A computer-aided computation shows that

$$\Delta_{E,\rho'}^N = t^4 + 2t^3 + 2t^2 + 2t + 1, \quad \Delta_{E,\rho'}^D = t^2 + 2t + 1.$$

Note that both $\Delta_{T,\rho'}^N$ and $\Delta_{T,\rho'}^D$ are symmetric.

In order to invoke Theorem 3.3, we compute the twisted Alexander polynomials of K_T . We are again aided by computer programs written by the authors, which enumerates all the representations $\rho: G(K_T) \rightarrow \mathrm{SL}(2, \mathbb{F}_5)$ (up to conjugation) and then computes the associated twisted Alexander polynomials. By this we obtain that there are exactly eight distinct twisted Alexander polynomials of $G(K_T)$ over $\mathrm{SL}(2, \mathbb{F}_5)$. These polynomials are listed in Appendix A.1, Table 1.

From Table 1, it is straightforward to verify that for any representation $\rho: G(K_T) \rightarrow \mathrm{SL}(2, \mathbb{F}_5)$, $\Delta_{K_T,\rho}^D \neq \Delta_{T,\rho'}^D$ or $\Delta_{K_T,\rho}^N$ does not divide $\Delta_{T,\rho'}^N$. By symmetry of the polynomials, the conclusion holds for $(\Delta_{T,\rho'}^N(t^{-1}), \Delta_{T,\rho'}^D(t^{-1}))$ as well. By Theorem 3.3, it follows that there is no meridional epimorphism of $G(K_T)$ onto $G(T)$.

3.3. Computation for J_{-1} and the figure eight knot

In this subsection we show that there is no meridional epimorphism of the knot group $G(J_{-1})$ onto the figure eight group $G(E)$, where J_{-1} is the knot described in Section 2.2.

For this case, we use representations over $\mathrm{SL}(2, \mathbb{F}_7)$. Let

$$\rho': G(E) = \langle y_1, y_2 \mid \bar{y}_1 \bar{y}_2 y_1 y_2 \bar{y}_1 y_2 y_1 \bar{y}_2 \bar{y}_1 y_2 \rangle \longrightarrow \mathrm{SL}(2, \mathbb{F}_7)$$

be the representation defined by

$$\rho'(y_1) = \begin{bmatrix} 0 & 4 \\ 5 & 2 \end{bmatrix}, \quad \rho'(y_2) = \begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix}.$$

The relator of $G(E)$ is sent to the identity, and we have

$$\Delta_{T, \rho'}^N = t^4 + t^3 + 3t^2 + t + 1, \quad \Delta_{T, \rho'}^D = t^2 + 5t + 1.$$

By computation aided by a computer, we obtain that there are exactly 139 representations up to conjugacy, and 58 distinct twisted Alexander polynomials of $G(J_{-1})$ over $\mathrm{SL}(2, \mathbb{F}_7)$. We list them in Table 2 in Appendix A.2. From Table 2 it is verified that for any representation $\rho: G(J_{-1}) \rightarrow \mathrm{SL}(2, \mathbb{F}_7)$, either $\Delta_{J_{-1}, \rho}^D \neq \Delta_{E, \rho'}^D$ or $\Delta_{J_{-1}, \rho}^N$ does not divide $\Delta_{E, \rho'}^N$. Since both $\Delta_{E, \rho'}^D(t)$ and $\Delta_{E, \rho'}^N(t)$ are symmetric, the conclusion holds for $(\Delta_{E, \rho'}^N(t^{-1}), \Delta_{E, \rho'}^D(t^{-1}))$ as well. By Theorem 3.3, it follows that there is no meridional epimorphism of $G(J_{-1})$ onto $G(E)$.

Remark 3.5. The most time-consuming step of the computation is to find all the representations of the given knot group. Our implementation performs a brute-force search; since its running time is exponential to the number of the generators, it would be interesting if a more clever algorithm is available. For $G(K_T)$, there is a presentation with 3 generators, and all the 37 $\mathrm{SL}(2, \mathbb{F}_5)$ representations (up to conjugacy) are found within a few seconds. For $G(J_{-1})$, we use a simplified presentation with 5 generators, and all the 139 $\mathrm{SL}(2, \mathbb{F}_7)$ representations (up to conjugacy) are found within 2 minutes. For $G(J_q)$ for $q \geq 1$ or $q < -1$, we could not derive any conclusion within resonable running time; computation for two weeks on a computer with a 3GHz Intel i7 processor was not enough.

4. Satellite construction and knot group epimorphisms

In this section we present a method to obtain infinitely many pairs of knots (K, K') for which $G(K')$ is a non-meridional homomorph of $G(K)$ but there is no meridional epimorphism $G(K) \rightarrow G(K')$. We will start with a given “seed” pair (K, K') of knots with the desired property, and then apply certain satellite constructions to produce infinitely many such examples.

4.1. Satellite construction and knot group epimorphisms

We begin by recalling the standard satellite construction. Let K be a knot in S^3 , and α is an unknotted oriented embedded circle in S^3 disjoint to K . Glue the exterior E_α of $\alpha \subset S^3$ and the exterior E_J of another knot J in S^3 along an orientation reversing diffeomorphism between the boundary tori, which identifies a zero-linking longitude and positively oriented meridian of α with a positively oriented meridian and zero-linking longitude of J , respectively. There is a diffeomorphism of the resulting 3-manifold onto S^3 , and the image of K under the diffeomorphism is a new knot, which we denote by $K(\alpha, J)$. In traditional terminology, J is the *companion* and K viewed as a knot in the

solid torus E_α is the *pattern*. As illustrated in Figure 6, $K(\alpha, J)$ is the knot obtained by “tying” J into K along a 2-disk bounded by α .

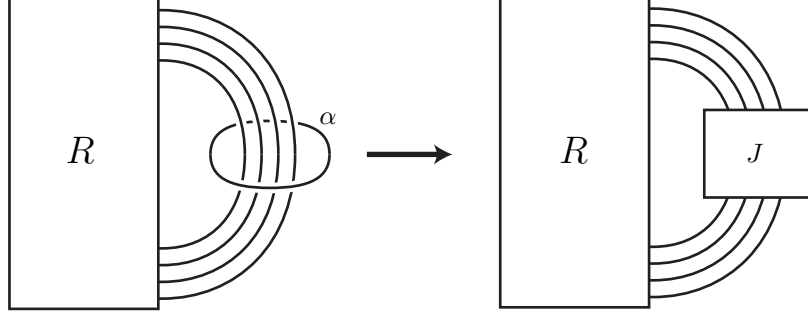


FIGURE 6. A satellite construction.

Note that $E_{K \sqcup \alpha}$ is a subspace of $E_{K(\alpha, J)}$ and a subspace of E_K . Let i_* and j_* be the inclusion-induced homomorphisms of $G(K \sqcup \alpha)$ into $G(K(\alpha, J))$ and $G(K)$, respectively. Then we have the following folklore:

Lemma 4.1. *There exists a meridional epimorphism $q: G(K(\alpha, J)) \rightarrow G(K)$ satisfying $i_* = q \circ j_*$.*

$$\begin{array}{ccc}
 & G(K(\alpha, J)) & \\
 j_* \nearrow & \downarrow q & \\
 G(K \sqcup \alpha) & & G(K) \\
 i_* \searrow & &
 \end{array}$$

For the reader's convenience, we give a proof.

Proof. There is a degree one map E_J to the trivial knot exterior $S^1 \times D^2$ which extends a diffeomorphism on the boundary sending the meridian and zero-linking longitude of J to those of the unknot. Glueing it with the identity map on $E_{K \sqcup \alpha}$, one obtains a degree one map $E_{K(\alpha, J)} \rightarrow E_K$ which induces the desired q . \square

We recall some standard definitions. The *derived subgroups* of a group G is defined inductively by $G^{(0)} = G$, $G^{(n+1)} = [G^{(n)}, G^{(n)}]$ where $[A, B]$ denotes the subgroup generated by commutators $\{aba^{-1}b^{-1} \mid a \in A, b \in B\}$. For the first infinite ordinal ω , the transfinite derived subgroup $G^{(\omega)}$ is defined by $G^{(\omega)} = \bigcap_{n < \omega} G^{(n)}$. A group G is *residually solvable* if $G^{(\omega)} = \{e\}$.

Remark 4.2.

- (1) The following well-known examples will be useful for our purpose: if K is a fibered knot (or link), then $G(K)$ is residually solvable. For, the commutator subgroup $G(K)^{(1)} = [G(K), G(K)]$ is the fundamental group of a surface with nonempty boundary, and thus a free group. It is known that a free group is residually solvable.
- (2) Not all knot groups are residually solvable. For example, the group of a nontrivial knot K with Alexander polynomial one is not residually solvable.

The key technical ingredient we use is the following.

Theorem 4.3. *Suppose T is a knot with residually solvable group $G(T)$. Suppose J has Alexander polynomial one. Then for any homomorphism $f: G(K(\alpha, J)) \rightarrow G(T)$, there is an induced homomorphism $f': G(K) \rightarrow G(T)$ that makes the following diagram commute:*

$$\begin{array}{ccccc}
 & & G(K(\alpha, J)) & & \\
 & \nearrow j_* & \downarrow q & \searrow f & \\
 G(K \cup \alpha) & & & & G(T) \\
 & \searrow i_* & \downarrow f' & & \\
 & & G(K) & &
 \end{array}$$

In addition, the following hold:

- (1) if f is an epimorphism, then f' is an epimorphism;
- (2) if f is meridional, then f' is meridional.

The following corollary is an immediate consequence.

Corollary 4.4. *If T and J are as in Theorem 4.3 and there is no meridional epimorphism of $G(K)$ onto $G(T)$, then there is no meridional epimorphism of $G(K(\alpha, J))$ onto $G(T)$.*

Proof of Theorem 4.3. Consider the composition

$$g: G(J) \longrightarrow G(K(\alpha, J)) \longrightarrow G(T).$$

Since J has Alexander polynomial one, the commutator subgroup $[G(J), G(J)]$ is perfect, i.e., $G(J)^{(1)} = G(J)^{(2)} = \dots = G(J)^{(\omega)}$. Since $g(G(J)^{(\omega)}) \subset G(T)^{(\omega)}$ and $G(T)$ is residually solvable, it follows that $G(J)^{(1)} \subset \text{Ker } g$. Therefore g factors through $G(J)/[G(J), G(J)] = \mathbb{Z}$.

From the construction of $K(\alpha, J)$, one sees that $G(K(\alpha, J))$ is the amalgamated product of $G(K \cup \alpha)$ and $G(J)$ over $\pi_1(S^1 \times S^1) = \mathbb{Z}^2$. The homomorphism

$$G(K(\alpha, J)) = G(K \cup \alpha) \amalg_{\mathbb{Z}^2} G(J) \longrightarrow G(K \cup \alpha) \amalg_{\mathbb{Z}^2} \mathbb{Z} = G(K)$$

induced by the abelianization $G(J) \rightarrow \mathbb{Z}$ is our q in Lemma 4.1. From the observation in the previous paragraph, it follows that $f: G(K(\alpha, J)) \rightarrow G(T)$ induces a homomorphism of $G(K)$. This proves the first conclusion.

From the commutative diagram the remaining conclusions follow immediately. \square

4.2. Infinitely many examples

Theorem 4.5. *Let T be the trefoil knot or the figure eight knot. Then there are infinitely many prime knots K_1, K_2, \dots satisfying the following:*

- (1) For each n there is an epimorphism $G(K_n) \rightarrow G(T)$ but there is no meridional epimorphism $G(K_n) \rightarrow G(T)$.
- (2) K_n and K_m are not equivalent for any $n \neq m$.

Remark 4.6. Due to Silver and Whitten [SW06], for prime knots there exists a meridional epimorphism if and only if there exists an epimorphism preserving peripheral subgroups. Therefore for our K_n in Theorem 4.5, there is no epimorphism $G(K_n) \rightarrow G(T)$ sending peripheral subgroups into peripheral subgroups.

Proof. Recall that we have constructed a prime knot K which admits an epimorphism $G(K) \rightarrow G(T)$ but does not admit any meridional epimorphism $G(K) \rightarrow G(T)$; when T is the trefoil, $K = K_T$ in Figure 1, and when T is the figure eight, $K = J_{-1}$ in Figure 5.

Choose an embedded circle α in $S^3 - K$ satisfying the following: α is unknotted in S^3 , α does not bound a 2-disk in E_K , and $K \cup \alpha$ is a prime link. For example, we may use α shown in Figures 4.2 and 4.2. Choose a hyperbolic nontrivial knot P with Alexander polynomial one; for example the knot **11n_34** in KnotInfo [CL] can be used as P . Let P_n be the connected sum of n copies of P . Let $K_n = K(\alpha, P_n)$.

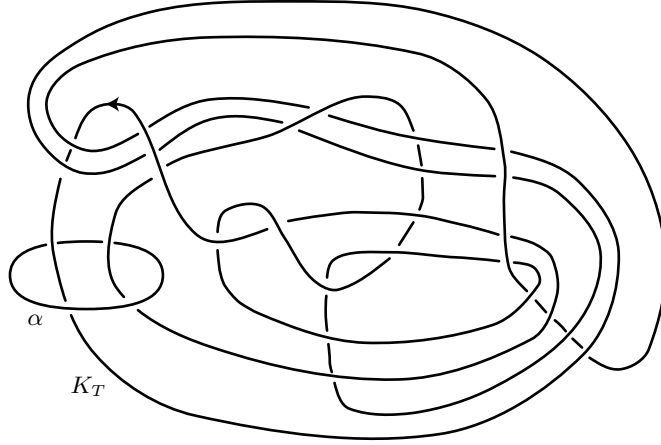


FIGURE 7. A curve α for a satellite construction on K_T . The link $K_T \cup \alpha$ is hyperbolic with volume 23.2123, according to SnapPy [CDW].

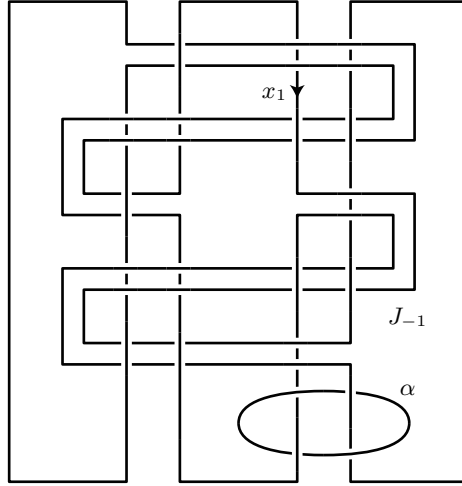


FIGURE 8. A curve α for a satellite construction on J_{-1} . The link $J_{-1} \cup \alpha$ is hyperbolic with volume 26.2914, according to SnapPy [CDW].

Note that $G(T)$ is residually solvable since T is fibered. Since the seed knot K satisfies the conclusion (1), our K_n satisfies (1) by Lemma 4.1 and Theorem 4.3.

To show that the K_n have distinct knot types, we consider the JSJ decomposition of the exterior. Indeed in most cases satellite constructions with distinct companion give distinct JSJ decompositions. In our case it can be seen as follows. The exterior of E_{K_n} is the union of $E_{K \cup \alpha}$ and E_{P_n} . Since P_n is a nontrivial knot and α does not bound a 2-disk in E_K , the boundary of E_{P_n} is an incompressible torus in E_{K_n} . Since P is hyperbolic, the JSJ tori of E_{K_n} are exactly the union of ∂E_{P_n} and the JSJ tori of $E_{K \cup \alpha}$ and E_{P_n} . In addition, since P_n is the connected sum of n copies of the hyperbolic knot P , the number of the JSJ tori of E_{K_n} is monotonically increasing. It follows that K_n and K_m have non-homeomorphic exteriors if $n \neq m$.

For the primality of the K_n , one may again look at the JSJ decomposition: since $K \cup \alpha$ is prime, the root piece in the JSJ decomposition of E_{K_n} is not a composition space and therefore K_n is not a composite knot.

Or alternatively, one can give a direct argument as follows: suppose there is a 2-sphere S in S^3 meeting K_n at two points. Let Σ be the boundary of $E_{J_n} \subset E_{K_n}$ and look at the intersection of S and Σ . An innermost circle C of $S \cap \Sigma$ must bound a 2-disk on Σ , since otherwise it would be a compressing disk of the incompressible torus Σ . So we can remove the intersection circle C by isotopying S in S^3 . Repeating this we may assume that S is disjoint to Σ . Now, S can be viewed as a 2-sphere in S^3 which meets K at two points and disjoint to α . Let B_1 and B_2 be the 3-balls obtained by cutting S^3 along S where $\alpha \subset B_1$. Since $K \cup \alpha$ is prime, $B_2 \cap K$ is an unknotted arc in B_2 . This shows that S does not give a nontrivial connected sum decomposition of K_n . \square

Appendix A. Tables of twisted Alexander polynomials

A.1. Twisted Alexander polynomials of K_T over $\text{SL}(2, \mathbb{F}_5)$

In this subsection we present all the twisted Alexander polynomials, associated to representations over $\text{SL}(2, \mathbb{F}_5)$, of the knot K_T shown in Figure 1.

We use a simpler presentation of $G(K_T)$ to find out all the representations. A straightforward simplification of the presentation of $G(K_T)$ used in Section 2.1 shows that x_1, x_6 , and x_{17} generate $G(K_T)$. In fact these three generators and the following relators form a presentation of $G(K_T)$:

$$\begin{aligned} & x_1 x_{17} \bar{x}_1 x_6 (x_{17} \bar{x}_6 x_1 \bar{x}_{17} \bar{x}_1)^3 x_{17} \bar{x}_1 \bar{x}_6 (x_1 \bar{x}_{17} x_1 x_{17} \bar{x}_1 x_6)^2 (\bar{x}_{17} x_1 x_{17} \bar{x}_1 x_6)^2 \bar{x}_{17} (\bar{x}_6 x_1 \bar{x}_{17} \bar{x}_1)^2 x_6, \\ & x_1 (\bar{x}_{17} x_1 x_{17} \bar{x}_1 x_6)^3 \bar{x}_{17} (\bar{x}_6 x_1 \bar{x}_{17} \bar{x}_1 x_{17})^4 \bar{x}_1 \bar{x}_6 x_1 (\bar{x}_{17} x_1 x_{17} \bar{x}_1 x_6)^4 (x_{17} \bar{x}_6 x_1 \bar{x}_{17} \bar{x}_1)^3 x_{17}. \end{aligned}$$

We use computer programs to find out all the representations over $\text{SL}(2, \mathbb{F}_5)$ and to compute the associated twisted Alexander polynomials. It turns out that there are exactly 19 representations modulo conjugacy, which give 8 distinct twisted Alexander polynomials. We list the 8 polynomials in Table 1. For each twisted Alexander polynomial in Table 1, we describe a representation $\rho: G(K_T) \rightarrow \text{SL}(2, \mathbb{F}_5)$ (which is not unique in general) which gives the polynomial by presenting the matrices $\rho(x_1)$, $\rho(x_6)$, and $\rho(x_{17})$.

TABLE 1. The twisted Alexander polynomials of the knot K_T in Figure 1 over $\text{SL}(2, \mathbb{F}_5)$.

$\rho(x_1)$	$\rho(x_6)$	$\rho(x_{17})$	$\Delta_{K_T, \rho}^N$	$\Delta_{K_T, \rho}^D$
$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$t^8 + t^7 + 4t^5 + 4t^4 + 4t^3 + t + 1$	$t^2 + 3t + 1$
$\begin{bmatrix} 2 & 4 \\ 4 & 1 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 4 & 1 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 4 & 1 \end{bmatrix}$	$t^8 + 4t^7 + t^5 + 4t^4 + t^3 + 4t + 1$	$t^2 + 2t + 1$
$\begin{bmatrix} 0 & 2 \\ 2 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 2 \\ 2 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 2 \\ 2 & 4 \end{bmatrix}$	$t^8 + 2t^7 + t^6 + 2t^5 + 4t^4 + 2t^3 + t^2 + 2t + 1$	$t^2 + t + 1$
$\begin{bmatrix} 0 & 2 \\ 2 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 4 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 1 & 3 \\ 4 & 3 \end{bmatrix}$	$t^8 + 2t^7 + t^5 + 3t^4 + t^3 + 2t + 1$	$t^2 + t + 1$
$\begin{bmatrix} 1 & 1 \\ 4 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \\ 4 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \\ 4 & 0 \end{bmatrix}$	$t^8 + 3t^7 + t^6 + 3t^5 + 4t^4 + 3t^3 + t^2 + 3t + 1$	$t^2 + 4t + 1$
$\begin{bmatrix} 1 & 1 \\ 4 & 0 \end{bmatrix}$	$\begin{bmatrix} 2 & 2 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 3 & 4 \\ 2 & 3 \end{bmatrix}$	$t^8 + 3t^7 + 4t^5 + 3t^4 + 4t^3 + 3t + 1$	$t^2 + 4t + 1$
$\begin{bmatrix} 3 & 2 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 3 & 2 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 3 & 2 \\ 0 & 2 \end{bmatrix}$	$t^8 + 3t^6 + 3t^4 + 3t^2 + 1$	$t^2 + 1$
$\begin{bmatrix} 3 & 2 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 3 \\ 3 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 3 \\ 3 & 0 \end{bmatrix}$	$t^8 + 4t^6 + t^4 + 4t^2 + 1$	$t^2 + 1$

A.2. Twisted Alexander polynomials of J_{-1} over $\text{SL}(2, \mathbb{F}_7)$

In this subsection we present all the twisted Alexander polynomials, over $\text{SL}(2, \mathbb{F}_7)$, of the knot J_{-1} given in Figure 5. We start with the standard Wirtinger representation of J_{-1} ; the generators are labeled by x_1, x_2, \dots, x_{32} , starting from the arc with an arrow in Figure 5. By simplifying the Wirtinger presentation, we obtain a deficiency one presentation of $G(J_{-1})$ whose generators are the Wirtinger generators $x_2, x_{10}, x_{19}, x_{22}, x_{30}$, and relators are the following 4 words:

$$\begin{aligned}
& x_{19}\bar{x}_{30}\bar{x}_{10}x_{30}\bar{x}_{19}x_{10}\bar{x}_2x_{30}x_2\bar{x}_{30}x_2\bar{x}_{10}x_{19}\bar{x}_{30}x_{10}x_{30}\bar{x}_{19}x_{10}\bar{x}_2\bar{x}_{30}x_2\bar{x}_{10}, \\
& x_{30}x_{19}\bar{x}_{30}\bar{x}_{10}x_{30}\bar{x}_{19}x_{22}(x_{30}\bar{x}_{19})^2(\bar{x}_{30}x_{19})^2\bar{x}_{30}\bar{x}_{22}x_{19}\bar{x}_{30}x_{10}x_{30}\bar{x}_{19}\bar{x}_{30}x_2\bar{x}_{10}x_{22}x_{10}\bar{x}_2, \\
& \bar{x}_{30}x_2\bar{x}_{10}x_{19}\bar{x}_{30}x_{10}x_{30}\bar{x}_{19}\bar{x}_{30}x_2\bar{x}_{10}x_{22}x_{10}x_2\bar{x}_{10}\bar{x}_{22} \\
& \quad \cdot (x_{10}\bar{x}_2x_{30}x_{19}\bar{x}_{30}\bar{x}_{10}x_{30}\bar{x}_{19})^2x_{10}\bar{x}_2x_{30}\bar{x}_{10}, \\
& x_{19}\bar{x}_{30}\bar{x}_{22}x_{19}\bar{x}_{30}x_{10}x_2\bar{x}_{10}\bar{x}_{22}x_{10}\bar{x}_2x_{30}x_{19}\bar{x}_{30}\bar{x}_{10}(x_{30}\bar{x}_{19}x_{22})^2x_{19}\bar{x}_{30}\bar{x}_{22}x_{19}\bar{x}_{30}x_{10}x_{30} \\
& \quad \cdot \bar{x}_{19}\bar{x}_{30}x_2\bar{x}_{10}x_{22}x_{10}\bar{x}_2\bar{x}_{10}x_{30}\bar{x}_{19}x_{22}(x_{30}\bar{x}_{19})^2\bar{x}_{30}.
\end{aligned}$$

Again, we use computer programs which enumerate all the representations of this presentation over $\text{SL}(2, \mathbb{F}_7)$ and compute the associated twisted Alexander polynomials. There are total 139 representations up to conjugation, from which 58 distinct twisted Alexander polynomials are obtained. The polynomials are listed in Table 2. For each polynomial in the tables, we also describe a representation ρ (which is not unique in general) which gives the polynomial.

Table 2: Twisted Alexander polynomials of the knot J_{-1} .

$\rho(x_2)$	$\rho(x_{10})$	$\rho(x_{19})$	$\rho(x_{22})$	$\rho(x_{30})$	$\Delta_{J_{-1}, \rho}^N$	$\Delta_{J_{-1}, \rho}^D$
$\begin{bmatrix} 0 & 4 \\ 5 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 4 \\ 5 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 2 & 2 \\ 3 & 0 \end{bmatrix}$	$t^8 + t^7 + 3t^6 + 5t^5 + t^4 + 5t^3 + 3t^2 + t + 1$	$t^2 + 5t + 1$
$\begin{bmatrix} 5 & 0 \\ 0 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 5 & 0 \\ 4 & 3 \end{bmatrix}$	$\begin{bmatrix} 3 & 0 \\ 4 & 5 \end{bmatrix}$	$\begin{bmatrix} 6 & 4 \\ 1 & 2 \end{bmatrix}$	$t^8 + 2t^6 + 3t^4 + 2t^2 + 1$	$t^2 + 6t + 1$

(continued on next page)

$\rho(x_2)$	$\rho(x_{10})$	$\rho(x_{19})$	$\rho(x_{22})$	$\rho(x_{30})$	$\Delta_{J_{-1},\rho}^N$	$\Delta_{J_{-1},\rho}^D$
(continued from previous page)						
$\begin{bmatrix} 5 & 0 \\ 0 & 3 \end{bmatrix}$	$\begin{bmatrix} 5 & 0 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 3 & 1 \\ 0 & 5 \end{bmatrix}$	$\begin{bmatrix} 1 & 4 \\ 5 & 0 \end{bmatrix}$	$\begin{bmatrix} 3 & 3 \\ 0 & 5 \end{bmatrix}$	$t^8 + 2t^7 + t^6 + 2t^5 + 4t^4 + 2t^3 + t^2 + 2t + 1$	$t^2 + 6t + 1$
$\begin{bmatrix} 0 & 4 \\ 5 & 5 \end{bmatrix}$	$\begin{bmatrix} 6 & 0 \\ 5 & 6 \end{bmatrix}$	$\begin{bmatrix} 1 & 4 \\ 6 & 4 \end{bmatrix}$	$\begin{bmatrix} 4 & 4 \\ 6 & 1 \end{bmatrix}$	$\begin{bmatrix} 6 & 1 \\ 0 & 6 \end{bmatrix}$	$4t^8 + t^7 + 4t^6 + t^5 + 2t^4 + t^3 + 4t^2 + t + 4$	$t^2 + 2t + 1$
$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 2 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 5 \\ 4 & 3 \end{bmatrix}$	$\begin{bmatrix} 1 & 4 \\ 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & 2 \\ 4 & 2 \end{bmatrix}$	$2t^8 + 6t^7 + 4t^6 + t^4 + 4t^2 + 6t + 2$	$t^2 + 4t + 1$
$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$t^8 + 4t^7 + t^6 + 5t^5 + 5t^3 + t^2 + 4t + 1$	$t^2 + 3t + 1$
$\begin{bmatrix} 4 & 0 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 6 & 6 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 5 & 5 \\ 5 & 1 \end{bmatrix}$	$\begin{bmatrix} 3 & 3 \\ 5 & 3 \end{bmatrix}$	$\begin{bmatrix} 4 & 0 \\ 4 & 2 \end{bmatrix}$	$2t^8 + 6t^7 + 4t^6 + t^4 + 4t^2 + 6t + 2$	$t^2 + t + 1$
$\begin{bmatrix} 5 & 0 \\ 0 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 6 & 2 \\ 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 4 & 2 \\ 4 & 4 \end{bmatrix}$	$\begin{bmatrix} 5 & 3 \\ 0 & 3 \end{bmatrix}$	$2t^8 + t^7 + 4t^6 + t^4 + 4t^2 + t + 2$	$t^2 + 6t + 1$
$\begin{bmatrix} 5 & 0 \\ 0 & 3 \end{bmatrix}$	$\begin{bmatrix} 6 & 5 \\ 5 & 2 \end{bmatrix}$	$\begin{bmatrix} 6 & 3 \\ 6 & 2 \end{bmatrix}$	$\begin{bmatrix} 6 & 3 \\ 6 & 2 \end{bmatrix}$	$\begin{bmatrix} 5 & 0 \\ 0 & 3 \end{bmatrix}$	$2t^8 + 4t^6 + 6t^4 + 4t^2 + 2$	$t^2 + 6t + 1$
$\begin{bmatrix} 4 & 0 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 4 & 3 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 0 & 4 \end{bmatrix}$	$\begin{bmatrix} 4 & 0 \\ 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 5 & 3 \\ 6 & 1 \end{bmatrix}$	0	$t^2 + t + 1$
$\begin{bmatrix} 0 & 6 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 6 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & 6 \\ 5 & 3 \end{bmatrix}$	$\begin{bmatrix} 1 & 3 \\ 3 & 3 \end{bmatrix}$	$\begin{bmatrix} 6 & 4 \\ 2 & 5 \end{bmatrix}$	$2t^8 + 2t^7 + 3t^6 + 5t^5 + 6t^4 + 5t^3 + 3t^2 + 2t + 2$	$t^2 + 3t + 1$
$\begin{bmatrix} 0 & 4 \\ 5 & 5 \end{bmatrix}$	$\begin{bmatrix} 4 & 2 \\ 5 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \\ 6 & 5 \end{bmatrix}$	$\begin{bmatrix} 5 & 4 \\ 5 & 0 \end{bmatrix}$	$\begin{bmatrix} 6 & 1 \\ 0 & 6 \end{bmatrix}$	$4t^8 + 5t^6 + 3t^4 + 5t^2 + 4$	$t^2 + 2t + 1$
$\begin{bmatrix} 0 & 6 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 2 & 6 \\ 5 & 5 \end{bmatrix}$	$\begin{bmatrix} 5 & 3 \\ 3 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 5 \\ 4 & 0 \end{bmatrix}$	$\begin{bmatrix} 3 & 5 \\ 5 & 4 \end{bmatrix}$	$6t^8 + 2t^7 + t^6 + 6t^5 + 4t^4 + 6t^3 + t^2 + 2t + 6$	$t^2 + 1$
$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$t^8 + 3t^7 + t^6 + 2t^5 + 2t^3 + t^2 + 3t + 1$	$t^2 + 4t + 1$

References

- [AL12] Ian Agol and Yi Liu, *Presentation length and Simon's conjecture*, J. Amer. Math. Soc. **25** (2012), no. 1, 151–187.
- [CDW] Marc Culler, Nathan M. Dunfield, and Jeffrey R. Weeks, *SnapPy, a computer program for studying the topology of 3-manifolds*, Available at <http://snappy.computop.org> (12/09/2014).
- [CL] Jae Choon Cha and Charles Livingston, *KnotInfo: table of knot invariants*, <http://www.indiana.edu/~knotinfo>, February 9, 2015.
- [Fox53] Ralph H. Fox, *Free differential calculus. I. Derivation in the free group ring*, Ann. of Math. (2) **57** (1953), 547–560.
- [GA75] Francisco González-Acuña, *Homomorphisms of knot groups*, Ann. of Math. (2) **102** (1975), no. 2, 373–377.
- [GAR01] F. González-Acuña and A. Ramírez, *Two-bridge knots with property Q*, Q. J. Math. **52** (2001), no. 4, 447–454.
- [GAR03] Francisco González-Acuña and Arturo Ramírez, *Epimorphisms of knot groups onto free products*, Topology **42** (2003), no. 6, 1205–1227.
- [HKMS11] Keiichi Horie, Teruaki Kitano, Mineko Matsumoto, and Masaaki Suzuki, *A partial order on the set of prime knots with up to 11 crossings*, J. Knot Theory Ramifications **20** (2011), no. 2, 275–303.
- [HS01] Jim Hoste and Patrick Shanahan, *Trace fields of twist knots*, J. Knot Theory Ramifications **10** (2001), 625–639.

- [HS10] Jim Hoste and Patrick D. Shanahan, *Epimorphisms and boundary slopes of 2-bridge knots*, Algebr. Geom. Topol. **10** (2010), no. 2, 1221–1244.
- [JL89] Dennis Johnson and Charles Livingston, *Peripherally specified homomorphisms of knot groups*, Trans. Amer. Math. Soc. **311** (1989), no. 1, 135–146.
- [Joh80] Dennis Johnson, *Homomorphisms of knot groups*, Proc. Amer. Math. Soc. **78** (1980), no. 1, 135–138.
- [KS05] Teruaki Kitano and Masaaki Suzuki, *A partial order in the knot table*, Experiment. Math. **14** (2005), no. 4, 385–390.
- [KS08] ———, *A partial order in the knot table. II*, Acta Math. Sin. (Engl. Ser.) **24** (2008), no. 11, 1801–1816.
- [KSW05] Teruaki Kitano, Masaaki Suzuki, and Masaaki Wada, *Twisted Alexander polynomials and surjectivity of a group homomorphism*, Algebr. Geom. Topol. **5** (2005), 1315–1324.
- [KSW11] ———, *Erratum to the article Twisted Alexander polynomials and surjectivity of a group homomorphism*, Algebr. Geom. Topol. **11** (2011), no. 5, 2937–2939.
- [LS12] Donghi Lee and Makoto Sakuma, *Epimorphisms between 2-bridge link groups: homotopically trivial simple loops on 2-bridge spheres*, Proc. Lond. Math. Soc. (3) **104** (2012), no. 2, 359–386.
- [ORS08] Tomotada Ohtsuki, Robert Riley, and Makoto Sakuma, *Epimorphisms between 2-bridge link groups*, The Zieschang Gedenkschrift, Geom. Topol. Monogr., vol. 14, Geom. Topol. Publ., Coventry, 2008, pp. 417–450.
- [Ril72] Robert Riley, *Parabolic representations of knot groups. I*, Proc. London Math. Soc. (3) **24** (1972), 217–242.
- [SW06] Dan Silver and Wilbur Whitten, *Knot group epimorphisms*, J. Knot Theory Ramifications **15** (2006), 153–166.
- [SW08] ———, *Knot group epimorphisms ii*, arXiv:0806.3223, 2008.
- [Wad94] Masaaki Wada, *Twisted Alexander polynomial for finitely presentable groups*, Topology **33** (1994), no. 2, 241–256.

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